Watershed Modeling Assessment of Marmaton River

Summary *Impairment of water quality is a major concern for streams and rivers in the central regions of the United States. TMDL establishes a watershed framework and set management targets to alleviate pollution from both point and nonpoint sources. For this study, we used a hydrologic modeling approach to holistically examine the effect of land use management, urbanization development, and agricultural practices on sediment and nutrient loadings in an agricultural watershed. AnnAGNPS simulation indicates that while point source dischargers contribute 8% of TN and 24% TP loadings to Marmaton River, agricultural nonpoint sources are the leading pollution source contributing 55% of TN and 49% of TP loadings to the river. Based on TMDL analysis and model simulation, to control TN loading, 3% of the watershed area needs to be targeted whereas 1% of the total area is required for TP reduction management. The areas that include in both nutrient managements are 1,159 ac. Targeting such areas can reduce approximately 22% of the required TN reduction. Likewise, managing these critical areas can also lead to a 29% reduction of the required TP loading.*

The 1972 Clean Water Act (CWA) establishes the goal for restoring and maintaining the ecological integrity of the Nation's waters. Nearly two decades after its enactment, water quality has been significantly improved by primary regulation on discernible point sources as they constitute a large portion of water quality problems and are easily rectifiable (Boyd, 2000; McKenzie, 2006). Since then, nonpoint source pollution, in particular from agriculture, has become the most leading source that impairs water quality today (USEPA, 1996; 2007). Nutrients and sediment, along with oxygen depleting substances and pathogens, are the top pollutants in the impaired waterbodies.

According to the CWA regulations, a waterbody that does not meet ambient water quality standards is considered "impaired". The CWA requires states to develop a watershed-based clean-up plan for each impairment. The cleanup plan and the process used to develop it is the Total Maximum Daily Load (TMDL).

The TMDL is a calculation of the maximum allowable load of a pollutant that a waterbody can receive daily from both point and nonpoint sources and still meet water quality standards (USEPA, 1999). Thus, watershed loading models are frequently used for water quality management and play a central role in the TMDL development. A watershed model is a collection of mathematical equations that best describe the generation, transformation, and transport of a pollutant in the environment. And it allows water quality managers to evaluate environmental impacts of various management plans.

Marmaton River Watershed is one of the state's five targeted watersheds selected to demonstrate the successful restoration of water quality and watershed management implementation. The selection criteria include the development of Watershed Restoration and Protection Strategies (WRAPS), presence of high priority TMDLs, and existence of long-term water quality and stream flow monitoring stations as well as some watershed modeling efforts (Arruda, 1993; KDHE, 2008).

<u>Background</u>

The Marmaton River Watershed, 410 mi^2, is located in the Marais des Cygnes River Basin near the border between Kansas and Missouri, and is within the Central Irregular Plains Ecoregion (Fig 1). Historically, the watershed was dominated by tallgrass prairies, accompanied with narrow oak-hickory forest along meandering stream corridors (Chapman et al., 2001).

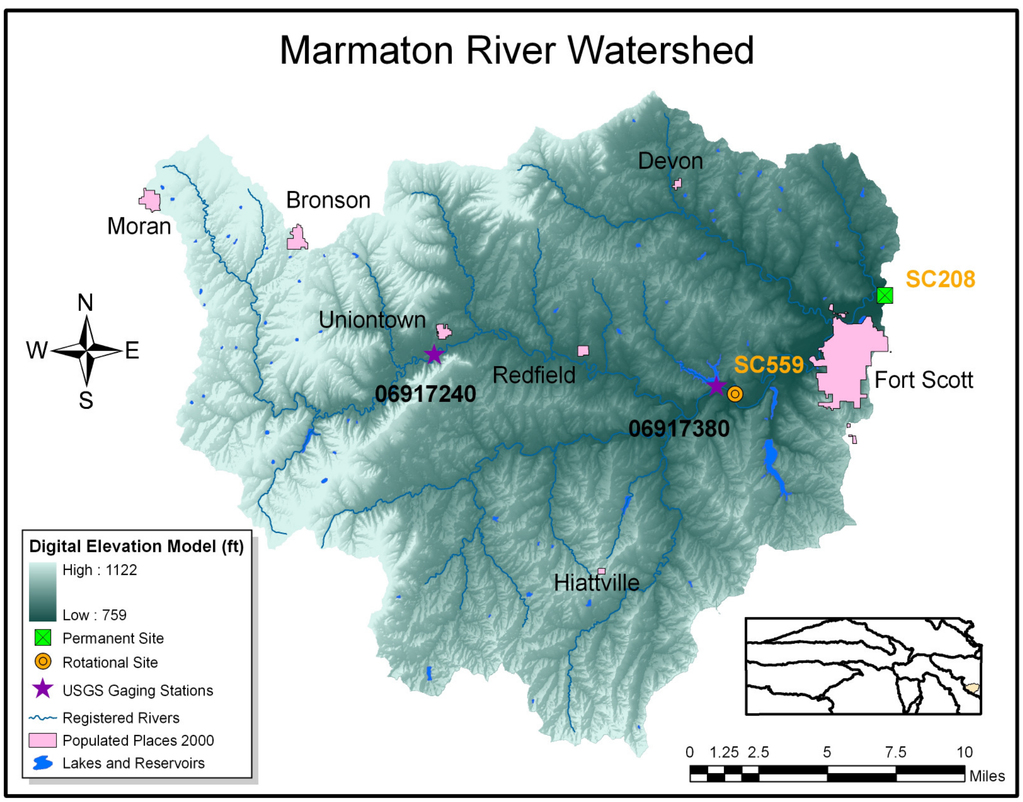

Fig1. The locations of water quality sampling sites and USGS gaging stations and major cites in the study watershed

Water Quality Impairment

Agricultural development began after the European settlement in the 1830s (MDC, 2008). Since then, riparian forests were cleared, corn and small grains were planted, livestock were raised, and streams were straightened. The expansion of agricultural production and a rapid urbanization from the last few decades has caused water quality problems in the recent years (Dodds and Oaks, 2004). As a result, the Kansas Department of Health and Environment identified the impairment of biology (or aquatic life) and dissolved oxygen (DO) for the Marmaton River in the 1998 303(d) list. Subsequently in 2001, two TMDLs were developed to address their associated water quality problems.

According to the TMDLs, excessive nutrients and/or oxygen demand materials along with sediment are identified as the main pollution sources and they are attributable to both point and nonpoint source pollution (KDHE, 2001a and 2001b). To control these pollutions, a 15% nutrient load reduction is required to achieve the water quality standards.

Land Use

The Marmaton River Watershed is predominantly agricultural, with approximately 67% of the land in pasture/hay (54%) and cultivated cropland (13%). Forest/Woodland and grassland each occupy about 13% of the total watershed area. Wetland area accounts only for less than 1% of the land. Fig 2 shows changes in land use between years 1992 and 2001. The percent area of cropland decreased from 1992 (30%) to 2001 (13%), whereas the percent urban area swiftly increased from about 1% in 1992 to 5 % in 2001. From 1992 to 2001, the increase in the percent pasture/hay area was close to double (Table 1).

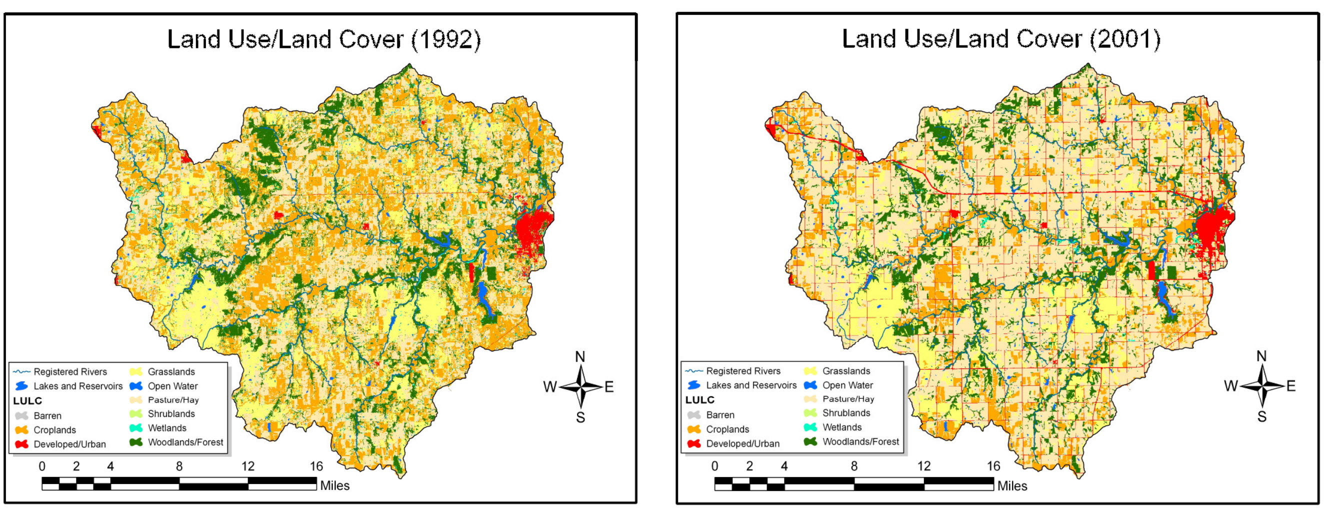

Fig 2. Changes in land use in the Marmaton River Watershed

Table 1. Changes in land use between 1992 and 2001

LULC	1992 (%)	2001 (%)	Difference (%)
Barren Land	0.02	0.02	19.67
Cropland	29.87	13.20	-55.80
Forest	14.73	12.86	-12.68
Grassland	16.65	12.92	-22.39
Shrub/Scrub	0.62	0.05	-91.92
Pasture/Hay	34.02	54.22	59.38
Urban	1.43	5.24	267.70
Water	0.92	0.88	-4.26
Wetland	1.74	0.59	-66.21

Soils

There are more than 20 soil series existed in the watershed. Catoosa series is the most dominant soil that occupies about 13% of the total area, followed by Zarr series (10%), Dennis (10%), and Parsons (8%) (Fig 3). Lanton series (poorly drained soil) occurs in 7% of the watershed area, which typically appears in alluvium on flood plains or depression areas.

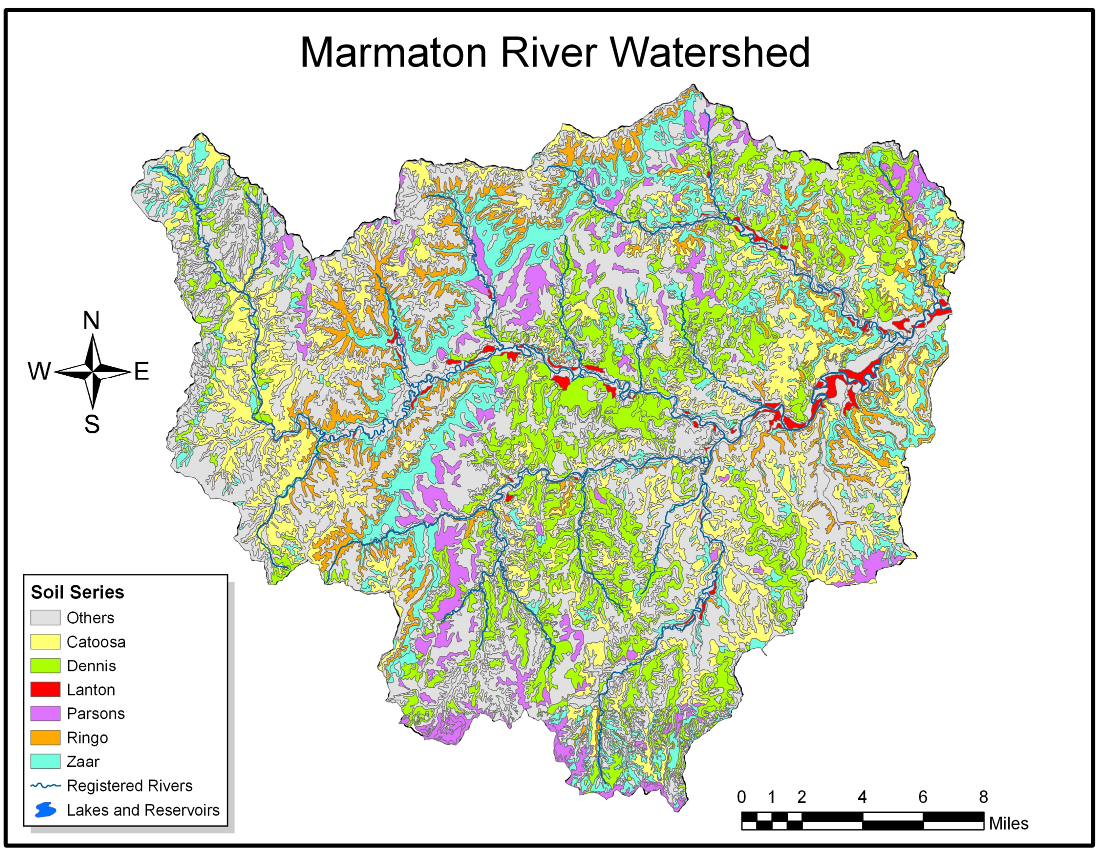

Fig 3. Major soil series in the Marmaton River Watershed

Fig 4 shows soil permeability values across the watershed, based on NRCS STATSGO database. The watershed-wide soil permeability averages 0.62"/hr. According to an USGS open-file report (Juracek, 2000), the threshold soil-permeability values that represent very high, high, moderate, low, very low, and extremely low rainfall intensity, were set at 3.43, 2.86, 2.29, 1.71, 1.14, and 0.57"/hr, respectively. The lower rainfall intensities generally occur more frequently than the higher rainfall intensities. The higher soil-permeability thresholds imply a more intense storm during which areas with higher soil permeability potentially may contribute runoff. Runoff is chiefly generated as infiltration excess with rainfall intensities greater than soil permeabilities. As soil profiles become saturated, excess overland flow is produced. Fig 5 displays calculated runoff potential, based on 1.14"/hr (1 = contributing areas; 0 = non-contributing areas). Under the extreme low (0.57"/hr) rainfall intensity (or runoff) condition, the potential contributing area is about 53%.

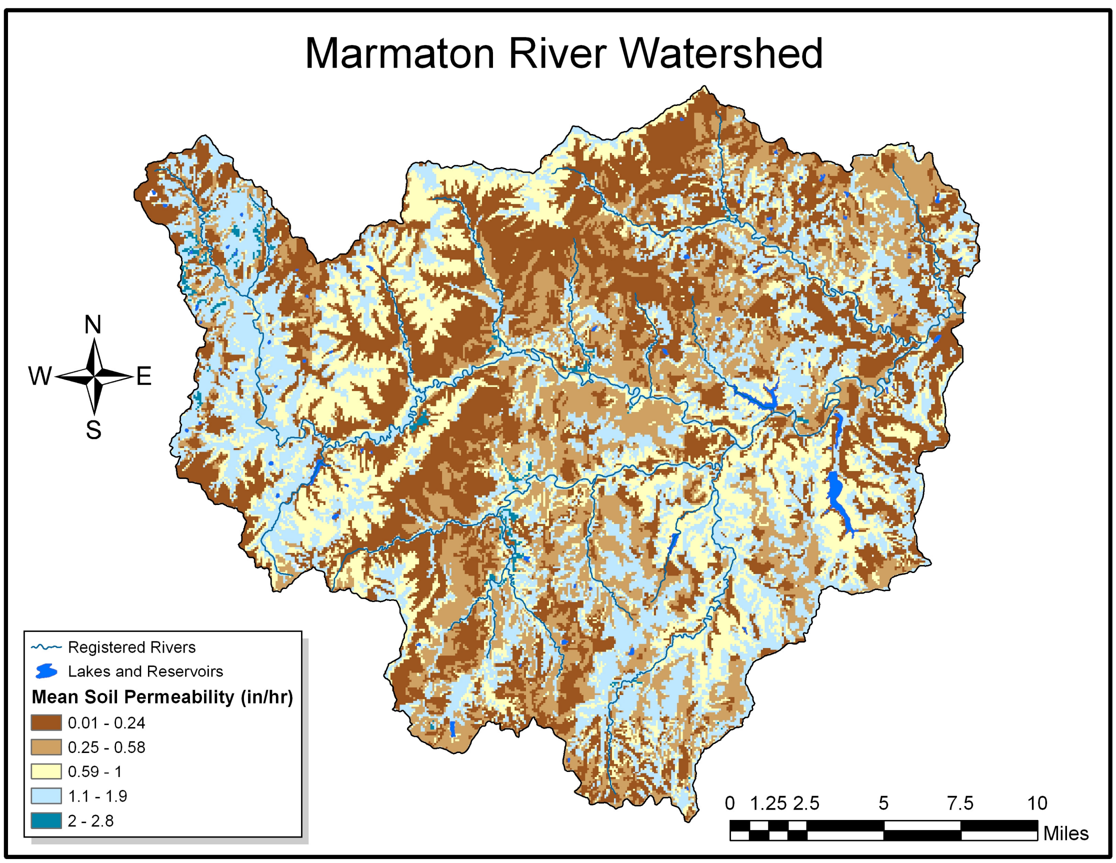

Fig 4. Mean soil permeability map

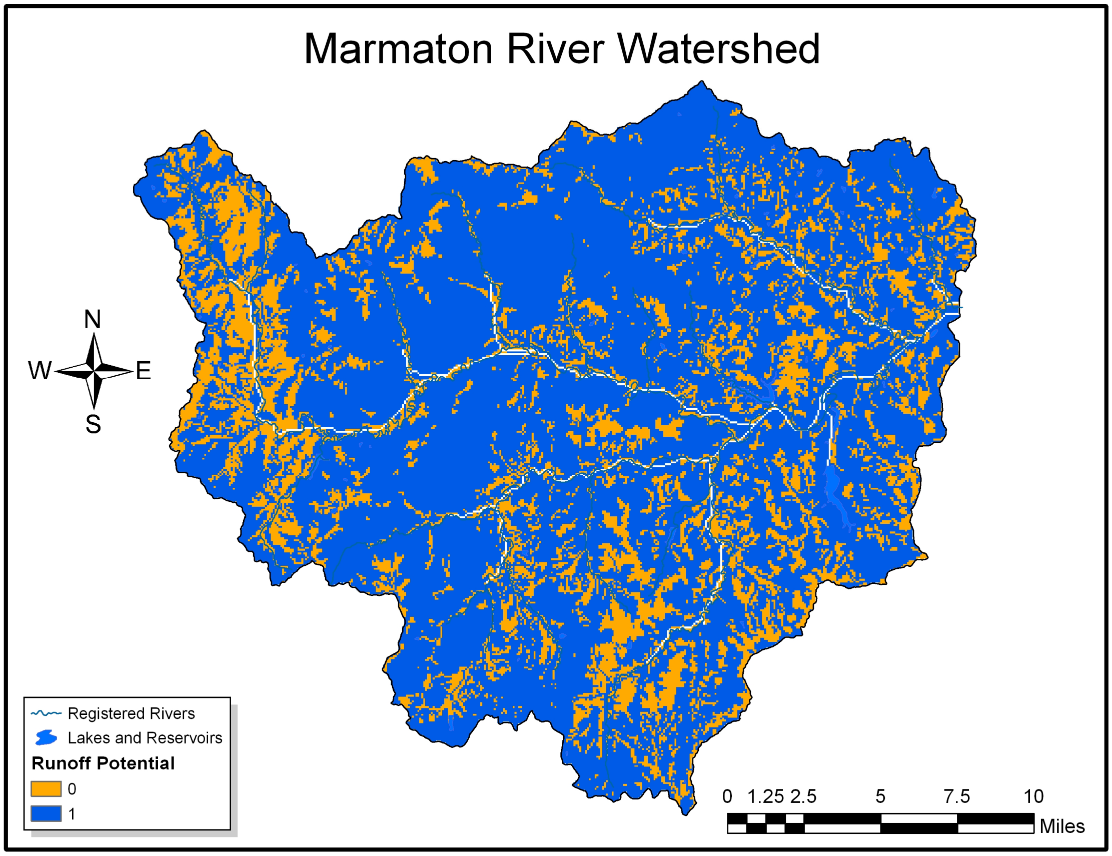

Fig 5. Runoff potential map

<u>Hydrology</u>
Two USGS gaging stations are located in the watershed (see Fig 1); Station 06917380 at Marmaton River near Marmaton, and Station 06917240 at Marmaton River near Uniontown. The drainage areas for these two stations are 292 mi^2 and 84 mi^2, respectively. Table 2 shows the estimated flow duration values. The median streamflow measured at Marmaton River near Marmaton is 38 cfs. The 10% flow exceedance is 440 cfs while the 90% flow exceedance is about 1 cfs. The contribution of runoff to the streamflow is 72%. The average runoff is 146,058 ac-ft, ranging from 34,855 ac-ft in 2000 to 324,719 ac-ft in 1985 (Fig 6). The amount of runoff on the watershed is 9.38 in (238 mm) during the period from 1972 to 2005.

Table 2. Estimated flow duration values for the two USGS gaging stations located in the Marmaton River Watershed

	Flow exceedance (cfs)					Runoff	History
	90th	75th	50th	25th	10th	(%)	
Marmaton	0.5	3.8	38.0	147.0	440.0	72	1972-2005
Uniontown	0.0	0.2	7.7	33.0	92.0	64	2001-2005

Note: Runoff calculation was based on local minimum method in the Web-based Hydrograph Analysis Tool developed by Dept. of ABE, Purdue University.

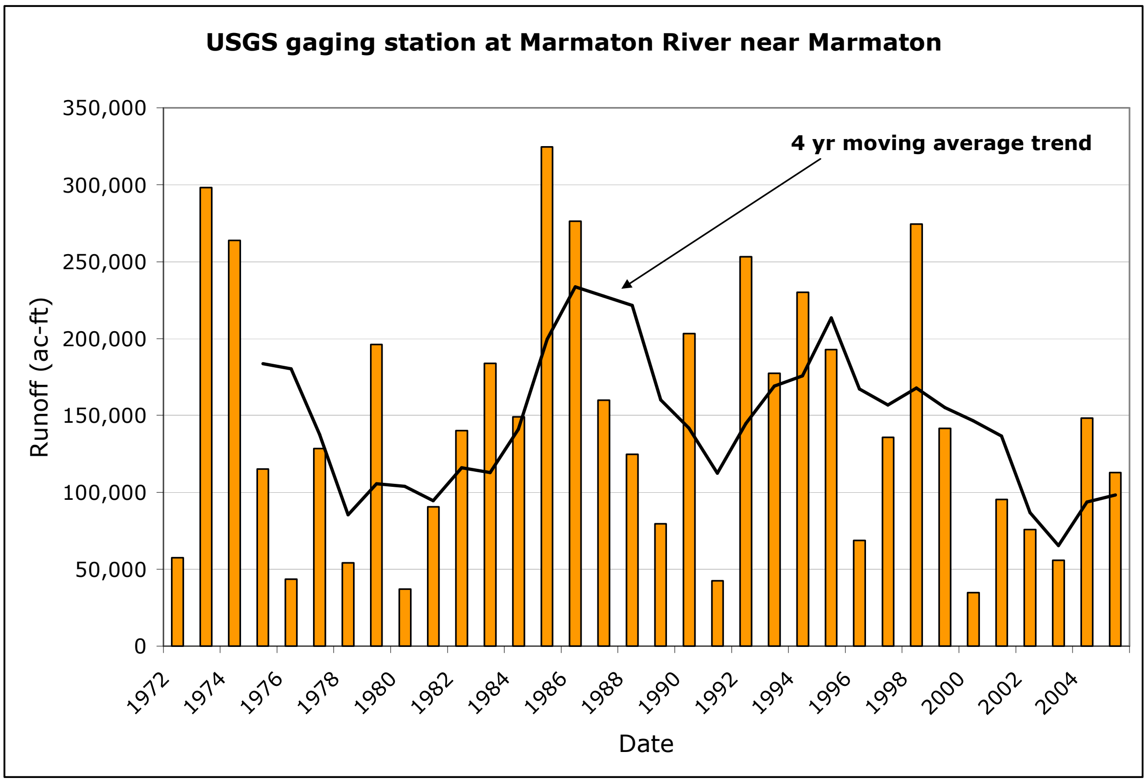

Fig 6. Runoff at USGS Station 06917380 near Marmaton in 1972-2005

Model Selection

Over the last three decades, there have been multitudes of watershed models developed to identify and quantify pollution sources and assess the effectiveness of best management practices (BMPs). In general, these models can be categorized into three groups, based on the levels of complexity of model components (USEPA, 1997; 1999). Simple models use the data generalized from many studies to estimate long-term average loads whereas detailed models simulate interactive watershed processes that affect pollution generation. Mid-range models are a compromise between the empiricism of the generalized models and the complexity of hydrologic simulation models. Reviews and evaluation of a few watershed models are provided in Benaman et al (2000), Bora and Bera (2003), USEPA (2003), and Parsons et al (2004).

Reasonable assurance, available resources, and adaptive management are key parts of the TMDL process where watershed model selection intersects the policy goals of the CWA (NRC, 2001; DePinto et al., 2004; USEPA, 2008). For example, the use of simple models, though might identify the sensitive areas (Nejadhashemi and Mankin, 2007), often does not provide reasonable assurances in describing how managing these areas would meet water quality standards since the CWA regulations do not require states to adopt regulatory measures on controlling pollution from nonpoint sources. In general, these models have very limited predictive capability (USEPA 1997). Mid-range and detailed models are typically used for assigning load allocation. TMDL modeling tasks are a phased or adaptive application that requires continuous data collection, model calibration/validation, and evaluation of implemented BMPs so that pollution sources can be progressively curtailed in rectifying impaired waterbodies. The conceptual relationship between model selection and water quality targets is illustrated in Fig 7.

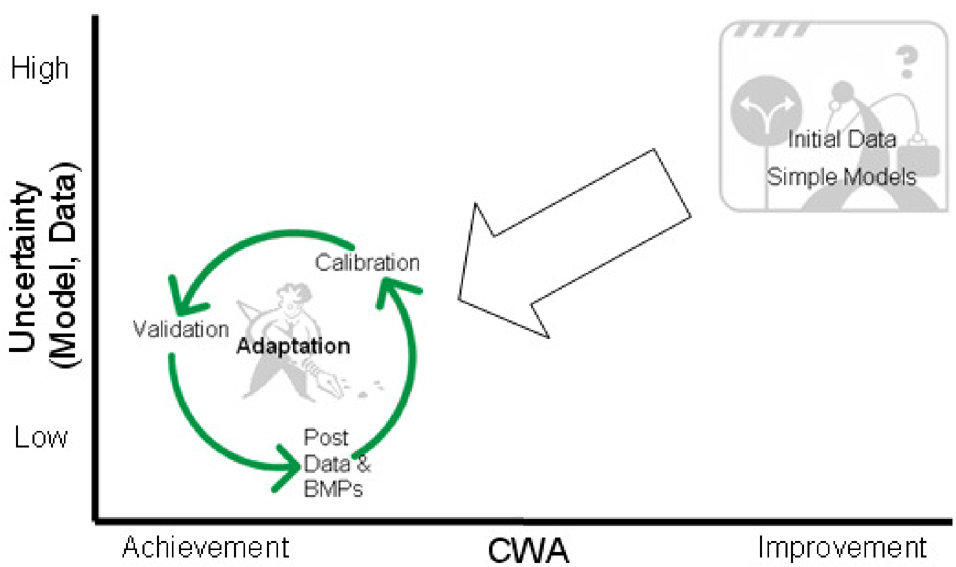

Fig 7. Conceptualized process of model selection

Soil and Water Assessment Tool (SWAT) and Annualized Agricultural Nonpoint Source model (AnnAGNPS) are detailed watershed models and suitable for estimating sediment and nutrient delivery and transport in agricultural watersheds. For this modeling study, AnnAGNPS model was selected because the former uses hydrologic response units (HRUs) to characterize subwatersheds yet the results of these HRUs are lumped together in the simulation. Thus, SWAT does not recognize the value of individual HRUs that can be evaluated and managed as target areas at local level. In general, SWAT is used for large watersheds or river basins.

<u>Model Description</u>

Annualized Agricultural Nonpoint Source model is a batch-process, continuous simulation, watershed-scale model specifically designed for agriculturally dominated watersheds (Wang et al., 2005; Shrestha et al., 2006; Polyakov et al., 2007). AnnAGNPS was jointly developed by the USDA Agricultural Research Service and Natural Resources Conservation services. This watershed model does distributed-modeling that divides a watershed into homogenous cells or subwatersheds (up to 10,000 acres) to quantitatively estimate runoff and sediment, nutrient and pesticide loading. The cells or drainage areas are irregular basins with uniform physical and hydrological characteristics; this approach allows analyses for any point within the watershed.

Since its inception, AnnAGNPS has been used as detailed applications such as assessing the effectiveness of best management practices (BMPs) or changes in land use patterns (Yuan et al., 2001). AnnAGNPS uses the Revised Universal Soil Loss Equation and Hydrogeomorphic Universal Soil Loss Equation to simulate soil and sediment loss from the field, and is able to estimate sediment and nutrient loss associated with ephemeral gullies. Earlier versions of this model (e.g., AGNPS), which are event-related models, have been broadly and successfully used in the central United States (e.g., Mankin and Kalita, 2000; Mankin and Koelliker, 2001; Mankin et al., 2003).

<u>Data Collection</u>

Table 3 summarizes available data used in the model for the study area. This data includes land use/land cover, elevation, streamflow, and stream water quality as well as stream geometry and field operation and management (e.g., fertilizer application and tillage). Ephemeral gully sites were initially identified using a GIS tool and later validated with field visits. Design flow and periodic water quality data of several wastewater treatment plants were also collected and used to determine point source nutrient loads.

Table 3. Available data and sources

Data Type	Description	Sources	Date
Land Use	Kansas GAP land cover, updated with FSA data	KBS/KARS	2001/2006
Water Quality	Bimonthly total suspended solids, total nitrogen (TN), total phosphorus (TP), dissolved N and dissolved P	KDHE	2000-2005
NPDES (WWTPs)	Municipal wastewater treatment plants	KDHE	2000-2005
Stream Geometry	Geomorphic assessments (Emmert & Hase, 2001)	KWO	2001
Weather	Daily climatic data (e.g., rainfall & temperatures)	NCDC	2000-2005
Ephemeral gullies	Aerial photos (National Agriculture Imagery Program)	USDA/FSA	2004
Soils	Soil Survey Geographic Database (SSURGO)	USDA/NRCS	2006
Crop Management	Scenarios management (TR-55)	USDA/NRCS	1986
Field Management	Field operation & management	USDA/NRCS	2006
DEM	National Elevation Dataset (30 m resolution)	USGS	1999
Streamflow	Daily streamflow	USGS	2000-2005

Abbreviation: KBS/KARS (Kansas Biological Survey/Kansas Applied Remote Sensing Program); NCDC (National Climatic Data Center); KWO (Kansas Water Office) USDA/FSA (US Dept of Agriculture/Farm Service Agency); NRCS (natural Resources Conservation Service); USGS (US Geological Survey)

Model Calibration & Validation

In watershed modeling, calibration and validation are an important evaluation process that provides the quality assurance of simulated data associated with measured conditions. While the calibration refers to adjusting model parameters to best represent a portion of the observed data, the validation is simply a comparison of the adjusted model's predictions to the rest of the measured data (Donigian, 2002). A guidance for quantifying accuracy of watershed simulation is recently presented by Moriasi et al (2007). For this study, both calibration and validation were performed on a monthly basis. Runoff, sediment, and TP were calibrated for a 36-month period from 2000 to 2002, and then validated in the same order for the remaining period from 2003 to 2005. Total nitrogen was calibration only for a 12-month period of 2002 and validated for a two-year period of 2003-2004. The coefficient of determination (R^2) and the Nash-Sutcliffe (NS) index values are widely used according to the guidance, and thus they were used for determining the accuracy of model predictions. The model calibration considered acceptable or satisfactory when its associated R^2 and/or NS values were greater than 0.5.

The results of calibration and validation for the Marmaton River Watershed are summarized in Table 4. The model calibration for all the parameters met the calibration guidance in despite that low R^2 and NS values were observed for TN. The monthly observed and simulated runoff, sediment and nutrients are shown in Fig 8, which provides detailed indication of model performance.

Table 4. Summary of model calibration and validation for monthly average runoff, sediment and nutrients

Model Parameter	Calibration				Validation			
	Obs	Sim	R^2	NS	Obs	Sim	R^2	NS
Runoff (in)	0.377	0.374	0.59	0.60	0.636	0.549	0.50	0.50
Sediment (lb/ac)	5.797	5.476	0.79	0.74	8.633	6.865	0.45	0.44
TN (lb/ac)	0.187	0.207	0.48	0.51	0.255	0.266	0.15	0.16
TP (lb/ac)	0.014	0.014	0.67	0.60	0.023	0.023	0.55	0.56

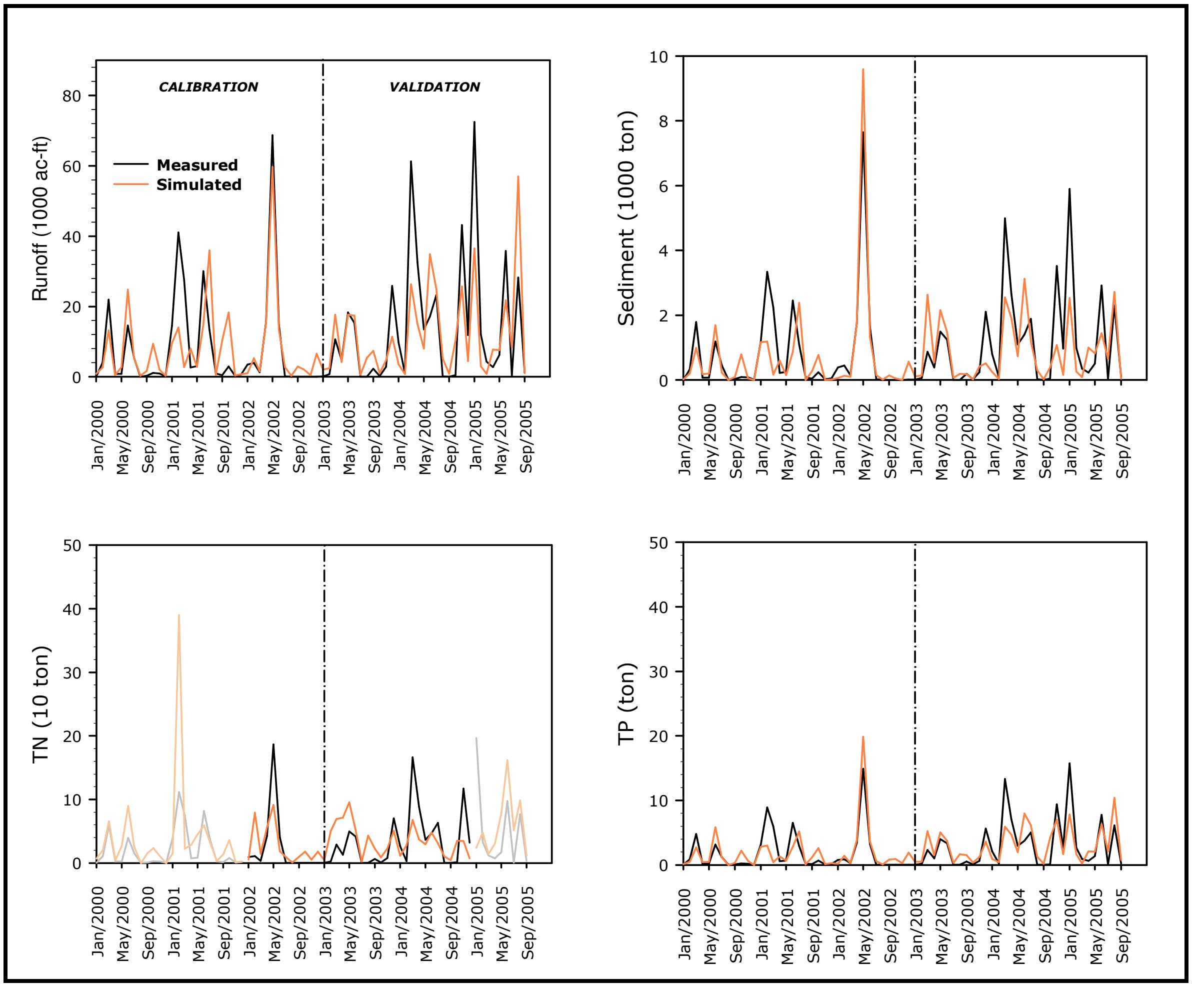

Fig 8. Monthly measured and simulated runoff, sediment, and nutrients over the calibration and validation period

Management Scenarios

Three management scenarios in addition to current conditions were simulated for the Marmaton River Watershed. Scenario 1 (Prairies) converted the entire watershed, except for the existing forest and woodland areas, to native tallgrass prairies to mimic the predevelopment hydrologic conditions. All point sources, impoundments, and fertilizer application were removed to minimize human influences. Scenario 2 (No BMPs) simulated the effect of removing conservation practices from the watershed. Currently, all the cultivated areas are under either terracing or contouring management. Scenario 3 (no-Till) simulated the effect of converting the current terrace/contour practices to no-till management. No-till farming system is a good soil management to improve soil fertility yet prevent water quality from degradation.

Results

Simulation of AnnAGNPS model indicated that cropland contributed most to the loading of sediment (3,728 tons/yr), TN (71.9 tons/yr), and TP (6.7 tons/yr) to the Marmaton River (Fig 9). Large amounts of sediment and nutrient loads also came from urban areas. Most of these point source loads were attributable to the effluents from the municipal wastewater treatment plants. The effluents from the wastewater treatment plants accounted for 17.6 tons of TN and 4.4 tons of TP to the river annually, which were 88% and 90% of the total point source loads, respectively. While the pasture/hay area contributed 14% of sediment, 24% of TN, 15% of TP, tallgrass prairies generated 9% of sediment, 18% of TN, and 13% of TP.

Table 5 shows the total watershed loadings of sediment, TN, and TP loads. During the years from 2000 to 2005, runoff accounted for 70% of the total streamflow and contributed 89% of sediment, 77% of TN, and 78% of TP transported to the Marmaton River whereas baseflow delivered 11% of sediment, 23% of TN and 22% of TP from the watershed.

Fig 9. Percent sediment, TN and TP loads of land use types

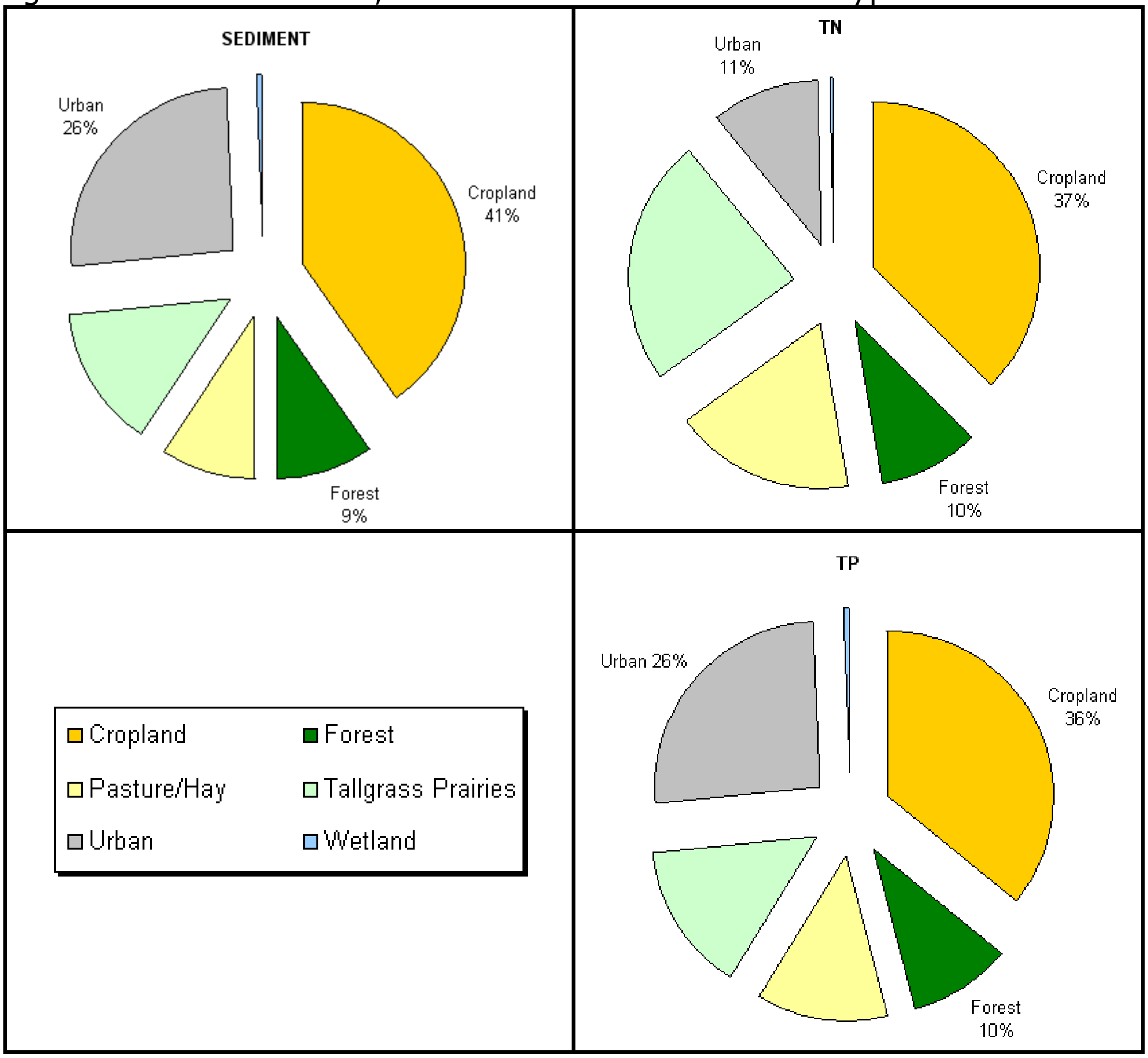

Table 5. Average annual total sediment and nutrient loadings during the years from 2000 to 2005

	RUNPFF	RUNOFF (%)	BASEFLOW	TOTAL
WATER (ac-ft)	115,303	70%	50,275	165,578
SEDIMENT (ton/yr)	9,266	89%	1,116	10,382
TN (lb/yr)	383,147	77%	117,515	500,662
TP (lb/yr)	37,488	78%	10,542	48,030

As indicated in Table 6, the presumed historic conditions increased the availability of the watershed to reduce sediment loss, as reflected in an 88% reduction in runoff events. The native conditions also reduced watershed TN load 80% and TP load 70%. Moreover, the historic prairie conditions reduced runoff by 19%. Removing all terraces and contours resulted in a 10% increase in runoff volume and produced an 11% increase in sediment load, 110% increase in TN load, and 11% increase in TP load. With no-till management, there was only a 1% decrease in runoff accompanied by a 2% reduction in sediment load, 6% in TN load and 1% in TP load.

Table 6. Summary of modeling results for watershed management scenarios, with removal efficiencies shown as percent values

Parameter	Current	Prairies		NO-BMPs		NO-Till	
Runoff (ac-ft)	115,303	93,573	-18.8%	126,892	10.1%	114,117	-1.0%
Sediment (ton/yr)	9,266	1,124	-87.9%	10,294	11.1%	9,100	-1.8%
TN (lb/yr)	383,147	76,847	-79.9%	801,552	109.2%	360,245	-6.0%
TP (lb/yr)	37,488	11,245	-70.0%	41,578	10.9%	36,954	-1.4%

Discussion

The model simulation clearly demonstrates that the existing implementation of the BMPs (i.e., terraces/contours) has reduced runoff in the Marmaton River, and helped control nutrients transported from the watershed to the river. The model simulation also captures the loading effect of the land conversion associated with agricultural production and a recent urbanization. Though the watershed is well managed, it still loses significant amounts of sediment and nutrients each year via runoff events. The losses of sediment and nutrients have degraded the water quality and affected biological communities in Marmaton River and may potentially influence downstream water quality. Based on the simulation results, agricultural nonpoint sources (i.e., cropland and pasture/hay) is the dominant pollution source that contributes approximately 55% of TN and 49% of TP while point source dischargers (i.e., wastewater treatment plants) account for 9% of TN and 24% of TP.

To control DO and biological water quality problems, the TMDL analysis suggests that a 15% load reduction in nutrients is required in order to meet the water quality standards. The implementation of no-till management is not sufficient to reduce nutrient loadings from the watershed (Table 6). Therefore, to improve water quality certain land retirement from the existing agricultural areas (e.g., NRCS Conservation Reserve Program) is needed and the restoration of wetlands is also suggested as indicated by a study of

Mitsch and Gosselink (2000) that 5% of wetland coverage is required in a watershed to remove N and 15% is necessary for retaining P. The wetlands in the Marmaton River Watershed only occupy about 1%. The lack of wetlands may be in part attributable to the rising degradation of water quality.

Though the wastewater dischargers are currently in compliance with their permit regulations, rapid development of urbanization poses a potential concern in water quality issues in the near future. The cites located within the watershed are responsible for protecting the environment within their associated jurisdictions. At present, the essential focus of management for the watershed is thus placed on regulating the nonpoint sources.

Fig 10 shows the target/critical management areas needed for a 15% load reduction for both TN and TP. These target areas account for approximately 3% of the total watershed area for TN (8,017 ac) and 1% of the watershed for TP (3,529 ac). The areas identified for both nutrient reduction managements are 1,159 ac. Targeting these areas can reduce approximately 22% of the required TN (26.5 tons or 52,995 lbs per year). Similarly, managing these critical areas can also lead to roughly a 29% reduction for the required TP (2.2 tons or 4,422 lbs per year).

The amount of TP loads for the targeting areas is closely associated with slope-length (LS) factor ($r = 0.75$, $p < 0.01$). The LS factor, a subfactor of the Revised Universal, is often used for evaluating sediment loss. It has been known that sediment is responsible for the majority of TP loading in agricultural runoff. Therefore, it is not unexpected to note that the longer LS value, the more TP is lost for the non-urban areas (Fig 11).

Unlike TP, there was no clear relationship existed between TN and LS. This result is likely due to the complex N transformation in soils, in particular nitrification and denitrification, and the dynamic inorganic and organic N transports in stream channels.

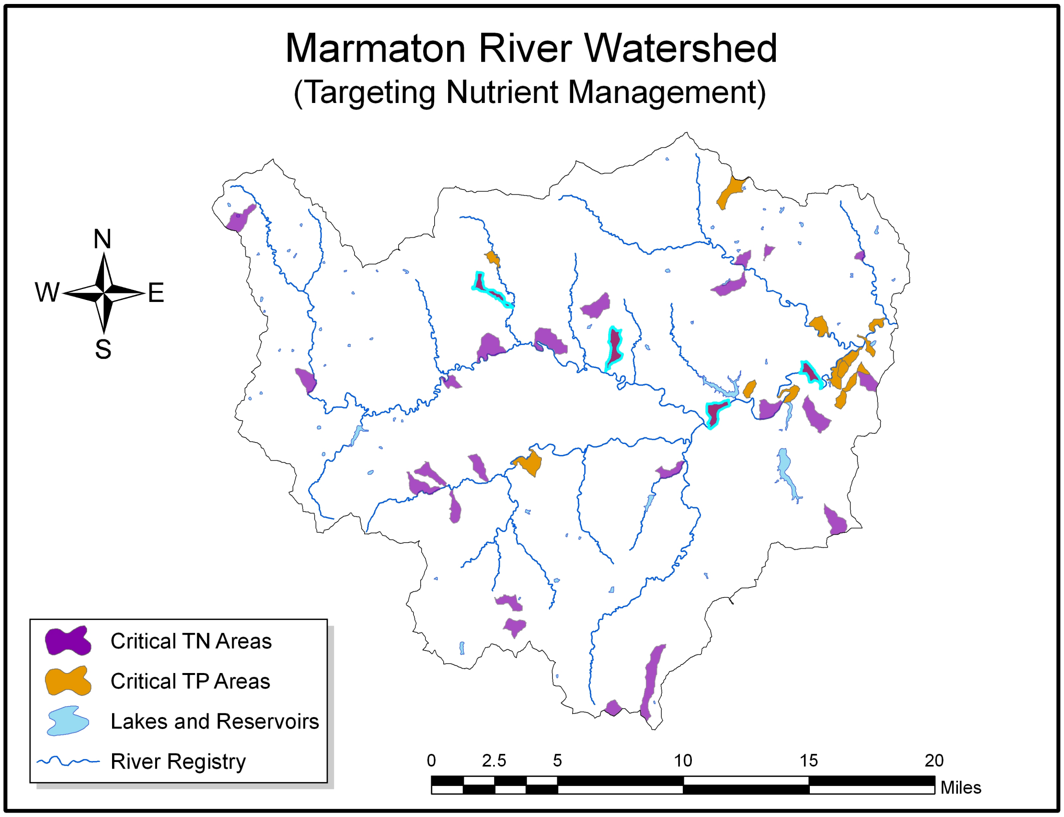

Fig10. Targeting nutrient management, with both TN and TP management areas highlighted

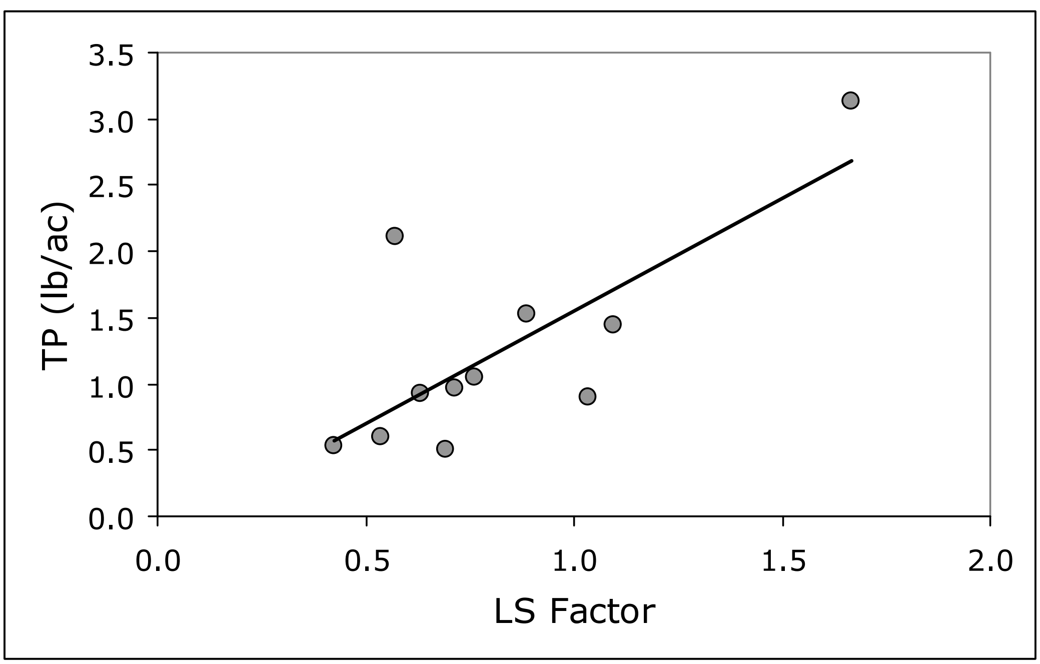

Fig11. Relationship between LS factor and TP loads at the non-urban management areas

Conclusion

The purpose of this study is to provide a comprehensive analysis of sediment and nutrient loadings using a modeling approach. Marmaton River and its tributaries are on the 303(d) list of impaired waterbodies for DO and biological communities. Nutrients, along with sediment and oxygen-depleting substances, are the major pollution source causing this water quality degradation, which predominantly come from agricultural areas.

AnnAGNPS model predicts better runoff, sediment, and TP values. Based on the TMDL analysis, a 15% load reduction is required to achieve the water quality standards. Point sources though may be responsible for water quality impairments, are required to comply with permit regulations. Therefore, the current management focus should be placed on controlling nutrient loadings from the diffuse sources. Certain land retirements from agricultural production and the restoration of wetlands are suggested management practices. While 3% of the watershed area needs to be targeted in order to remove TP, 1% of the total area is required to control TN transported from the watershed.

The study demonstrates that the application of hydrologic modeling is a holistic step in determining the effect of land use management, wastewater treatment, and agricultural practices, and is also an essential task in assessing load allocation, and determining critical areas. Moreover, it helps develop a suitable water quality improvement plan and allows managers or stakeholders to re-assess their targeted implementation in the future.

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